tion of condition for gases, and the two equations that result from the two fundamental theorems of thermodynamics. By means of these equations together with the necessary boundary conditions and the data relative to external influences, the problems of dynamic meteorology become definite formulated problems from a mathematical point of view. Theoretically speaking, they can now be attacked both qualitatively and quantitatively with some hopes of success.

The theoretical treatment of meteorological problems has kept pace with the development of observational meteorology and theoretical physics. At first idealized phenomena were discussed. By making appropriate assumptions, one or more variables may be eliminated, and thus one may devise problems of a purely dynamic or of a purely thermodynamic character. By still further simplifying assumptions we obtain corresponding simple integrable systems of equations whose solutions are essential to the comprehension of various meteorological phenomena. Ferrel, Guldberg and Mohn, Helmholtz, Hertz, Von Bezold, and others have given us valuable works of this character. To a certain extent Hann's theoretical works are also related to this class, since they aim at more precise general elementary explanations of meteorological phenomena.

All these works antedate the founding of modern aerology. But now that complete observations from an extensive portion of the free air are being published in a regular series, a mighty problem looms before us and we can no longer disregard it. We must apply the equations of theoretical physics not to ideal cases only, but to the actual existing atmospheric conditions as they are revealed by modern observations. These equations contain the laws according to which subsequent atmospheric conditions develop from those that precede them. It is for us to discover a method of practically utilizing the knowledge contained in the equations. From the conditions revealed by the observations we must learn to compute those that will follow. The problem of accurate pre-calculation that was solved for astronomy centuries ago must now be attacked in all earnest for meteorology.

The problem is of huge dimensions. Its solution can only be the result of long development. An individual investigator will not advance very far, even with his greatest exertions. However, I am convinced that it is not too soon to consider this problem as the objective of our researches. One does not always aim only at what he expects soon to attain. The effort to steer straight toward a distant, possibly unattainable point, serves, nevertheless, to fix one's course. So, in the present case, the far-distant goal will give an invaluable plan of work and research.

Here I may be permitted to draw an illustration from my personal experience. For many years I had already occupied myself with the application of the laws of hydrodynamics to the motions of the atmosphere, and had come to many interesting results. But the question kept recurring to me: What is it that I really seek? Whither am I steering? I could not free myself from the thought that "There is after all but one problem worth attacking, viz, the precalculation of future conditions."

As I had been able to find enthusiastic young colaborers who had the courage to follow me, I determined to always steer directly toward this distant goal.

We have never regretted it. To be sure the work we have already accomplished seems but to emphasize how far removed our goal really is. Yet our work has always been fruitful. Precisely because we have always kept the end clearly before us, we have been able to clearly formulate a whole series of preparatory individual problems, and to solve them one after the other. I can not go into details here. I will give but one example.

Obviously the usual mathematical methods will not be adapted to a problem of this sort. There can be no thought of an analytical presentation of the observational results with a subsequent analytical integration of the equations. As the observations are presented by means of charts, therefore all mathematical computations must be recast into graphical operations by means of maps. In this way we have developed for ourselves the rudiments of a graphical mathematics by means of which we derive one map from the other, just as one usually derives one equation from another by calculation. The steady development of the methods, which the novelty of our problem makes necessary, gives the work a peculiar charm which we would not forego. I hope that during my work here in Leipzig I may interest many younger colaborers in the abundant problems we meet with in this work.

Before closing I must touch upon an objection which is brought against our work. Our problem is, of course, essentially that of predicting future weather. "But," says our critic, "How can this be of any use? The calculations must require a preposterously long time. Under the most favorable conditions it will take the learned gentlemen perhaps three months to calculate the weather that nature will bring about in three hours. What satisfaction is there in being able to calculate to-morrow's weather if it takes us a year to do it?"

To this I can only reply: I hardly hope to advance even so far as this. I shall be more than happy if I can carry on the work so far that I am able to predict the weather from day to day after many years of calculation. If only the calculation shall agree with the facts, the scientific victory will be won. Meteorology would then have become an exact science, a true physics of the atmosphere. When that point is reached, *then* the practical results will soon develop.

It may require many years to bore a tunnel through a mountain. Many a laborer may not live to see the cut finished. Nevertheless this will not prevent later comers from riding through the tunnel at express-train speed.

PECULIARITIES OF THE CALIFORNIA CLIMATE.

EXPLAINED ON THE BASIS OF GENERAL PRINCIPLES OF ATMOSPHERIC AND OCEANIC CIRCULATION.

By George F. McEwen,

Oceanographer of the Scripps Institution for Biological Research.

[Dated January 5, 1914.]

INTRODUCTION.

In the report on the scientific results of the Challenger Expedition, Buchan (1) concluded his discussion of atmospheric circulation with the following statement:

> The isobaric maps show, in the clearest and most conclusive manner, that the distribution of the pressure of the earth's atmosphere is determined by the geographical distribution of land and water in their relation to the varying heat of the sun through the months of the year; and since the relative pressure determines the direction and force of the prevailing winds, and these in turn the temperature, moisture, rainfall, and in a very great degree the surface currents of the ocean, it is evident that there is here a principle applicable not merely to the present state of the earth, but also to different distributions of land and water in past times.

In the present paper an attempt is made to show the effect of the difference in temperature between land and water in modifying the distribution of atmospheric pressure and winds; and on the basis of these results, with the aid of Ekman's theory (**3**) of oceanic circulation, to account for the low-surface temperature along the west coasts of continents, special reference being made to the coast of California.

The contents of this paper fall under the following nine heads:

I. Preliminary explanation of atmospheric circulation on a non-rotating globe, and of the deflecting force due to the earth's rotation.

II. Ferrel's theory of atmospheric circulation on a smooth rotating spheroid.

III. Review of theories that have been proposed to account for the origin of the *ocean highs* (or areas of high air pressure on the ocean).

IV. A modified theory of the origin of the ocean highs.

V. Discussion of the causes of ocean temperatures either greater or less than the average for the latitude.

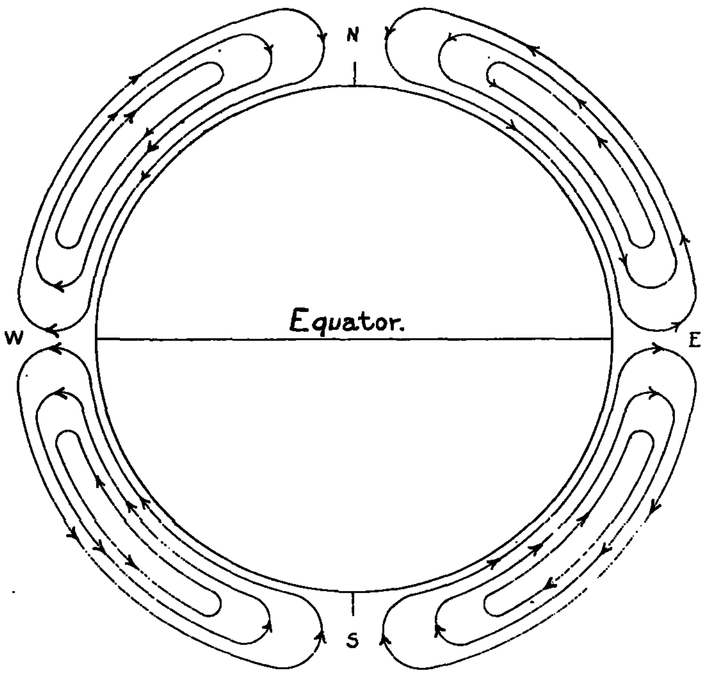

FIG. 1.—Condition of atmosphere under elementary hypothetical conditions.

VI. Ekman's theory of oceanic circulation, and its application to *upwelling*.

VII. The relation of winds parallel to a coast, the form of the bottom, *upwelling*, and surface temperatures off the coast of California.

VIII. Résumé and final applications of the preceding results.

IX. Summary.

I.—PRELIMINARY EXPLANATION OF ATMOSPHERIC CIRCULATION ON A NON-ROTATING GLOBE, AND OF THE DEFLECTING FORCE DUE TO THE EARTH'S ROTATION.

Assume the earth to be a smooth non-rotating sphere, having a homogeneous surface [and that an] excess of temperature [is maintained] at the equator would expand the air, thus causing the upper part to overflow toward the poles. This removal of the upper air from the equatorial to the polar regions would decrease the pressure at the equator and increase it at the poles, thus giving rise to a return current of the lower air along meridians toward the equator. Thus there would be a steady circulation maintained by the action of the *pressure gradient* (**25**), against the frictional resistance, in which the horizontal area of upward convection would be approximately equal to that of the downward movement. Since half of the earth's area lies between the circles of latitude 30° north and 30° south, therefore these circles would divide the atmosphere into an equatorial region of ascending currents and two polar regions of descending currents. (See fig. 1.)

Ferrel (**6**) appreciated the importance in problems of atmospheric circulation of the tendency of bodies in motion to curve to the right in the northern hemisphere and to the left in the southern hemisphere. This tendency is a consequence of the *deflecting force due to the earth's rotation* (**6**); because of its frequent application to the problems in this paper, an explanation of the principle is given now.

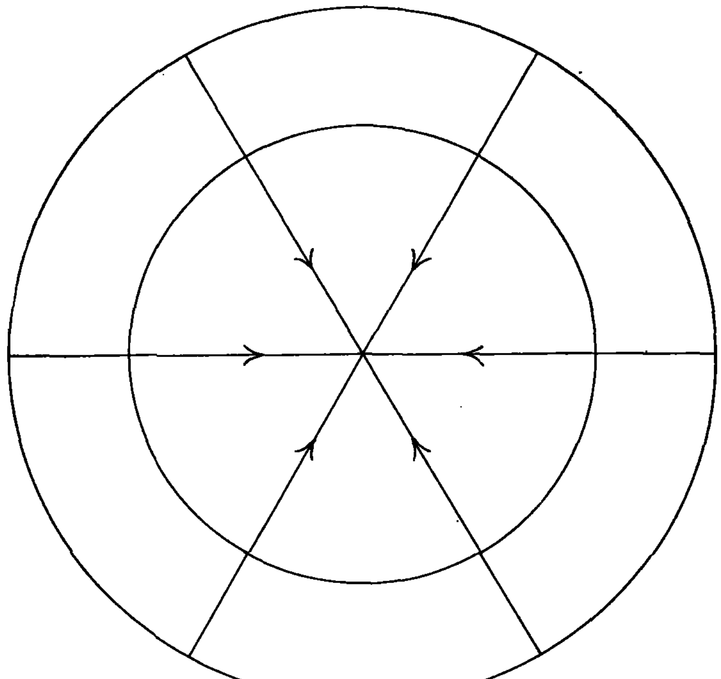

FIG. 2.—Gravitation and the ideal sphere.

Suppose the earth to be a plastic mass, homogeneous with reference to its center, and subject to the mutual gravitation of its parts. On the assumption of no rotation our planet would take a true spherical form, and the attractive force of gravity would act along lines through the center, and therefore perpendicular to any spherical surface having the same center. Under certain conditions the pressure would increase along a radius from the surface to the center, in order to balance the attractive forces. The sphere would then be called the figure of equilibrium of the earth, and its spherical boundary would be called a *level surface*, since the force of gravity would be perpendicular to the surface at each point (**26**).

Now suppose the earth to rotate about its axis **NS** (fig. 3). Then at each point of the mass an additional force would be required to maintain the spherical form. That is, in order to keep any particle **B** moving in a circular path of radius **BC** it would have to be continually pulled toward **C**, the center of the path; but if, at any time, both gravity and centrifugal force should cease to act upon the particle, it would continue to move with a constant velocity along a straight line tangent to the circular path at that point.

In the case of the gravitating plastic globe, the only available force for holding the particles in their circular paths is gravity. Suppose this centripetal force **F** is subtracted from the force of gravity **G** leaving the effective, or apparent attractive force **G'**; then we must replace **G** by **G'** throughout. (See fig. 4.)

But **G'** would not be perpendicular to the original spherical surface, which would therefore not be level. Hence, the mass being plastic, the apparent or effective forces would so mold the sphere that its surface would be everywhere perpendicular to them, and the oblate spheroid shown by the dotted line **N'BE'S'** would result (fig. 4). The modification of the original spherical form would increase in proportion to the velocity of rotation and the plasticity of the mass, thus to each velocity of rotation would correspond a different figure of equilibrium.

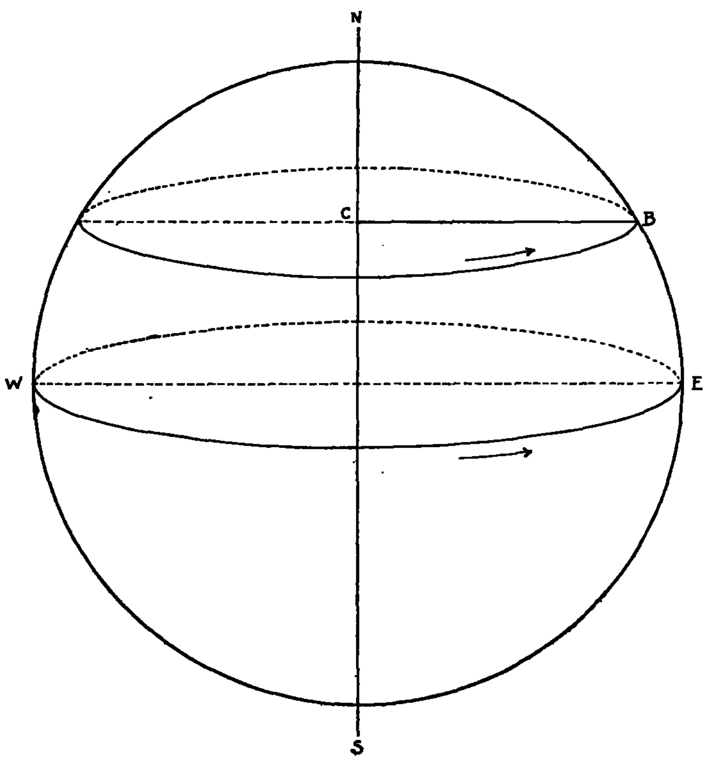

FIG. 3.—The earth, a rotating spheroid.

Neglecting comparatively slight irregularities of its surface, the earth is an oblate spheroid, corresponding very closely to the figure of equilibrium which would result from its present angular velocity: for many theoretical purposes it may be regarded as a true spheroid having a homogeneous surface. A particle at rest on such a rotating body would be in equilibrium.

But if the particle was forced to slide along the surface, for example to the east, an additional force perpendicular to the axis **NS** (fig. 4) would be required to hold it in this circular path, since its actual velocity in space would be greater than that of the earth's surface for that circle of latitude. If this force was subtracted from the apparent force of gravity **G'**, the resulting force would have a component tangent to the earth's surface and directed toward the equator, as can be seen by reasoning as before. While if the particle was moved to the west it would be forced toward the pole.

From another principle of mechanics, the *conservation of areas*, the effect of the earth's rotation on motion along a meridian can be determined. According to this principle, a line from a moving particle perpendicular to the earth's axis will describe equal areas in equal times as it rotates, unless a force not passing through the axis is applied. In other words the product of the actual eastward velocity of the rotating particle **B** (fig. 3) by its distance **BC** from the earth's axis must be constant [unless] a force acts on the particle in an east or west direction. Hence, when a particle on the earth's surface is forced toward the nearest pole **N** or **S**, the velocity to the east must increase, while if forced in the opposite direction the eastward velocity must decrease, since in the first case the distance from the particle to the axis is decreasing, while in the latter case it is increasing.

The above results may evidently be reduced to the following rule: Whenever a body moves along the earth's surface it becomes acted upon by a force directed to the right of the motion in the northern hemisphere, as shown by figure 5, but to the left in the southern hemisphere.

Analytical mechanics shows that the magnitude of this deflecting force ($2\,\omega\,v\sin\theta$) is proportional to the velocity

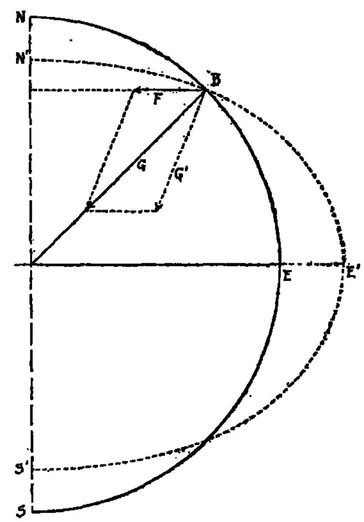

FIG. 4.—Gravitation and centrifugal force.

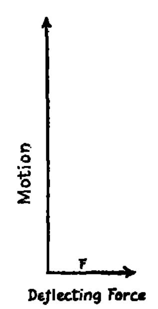

FIG. 5.—Constrained motion on the surface of the rotating spheroid.

of the body, and increases with the latitude, from zero at the equator to a maximum at the poles.

II.—FERREL'S THEORY OF ATMOSPHERIC CIRCULATION ON A SMOOTH ROTATING SPHEROID (27).

The general scheme of atmospheric circulation obtained by averaging the observed wind velocity for each of a series of parallels of latitude is shown by figure 6, while the distribution of pressure (28) obtained in the same way is represented by figure 7. The latter diagram represents a vertical section of the atmosphere by a plane through a meridian, which, for convenience, is represented by the straight line **N E S**. Each curve shows the relation of the pressure to the latitude at the elevation indicated on the right.

Now, by means of the two great facts on which this motion depends, namely, the relatively high equatorial temperature and the deflecting force due to the earth's rotation, we can explain the main features of atmospheric circulation and pressure distribution. The upper air over the equator tends to overflow along the meridian toward the poles, owing to the expansion due to the heated surface below, but in the northern hemisphere the overflow is deflected to the right, and were there no friction, would move to the east in a direction perpendicular to the meridional barometric gradient, which would then balance the deflecting force. But, since the air is a viscous fluid this motion to the east, if started, could not continue owing to the frictional resistance, which would decrease the velocity and therefore the deflecting force. The air would then be forced to the north because of the unchanged pressure gradient. Therefore, because of friction, the air actually moves to the north of east with such a velocity that the deflecting force and the resistance are in equilibrium with the gradient.

Thus the upper air moves spirally from the equator toward two poles with a relatively large eastward component, owing to the comparatively small amount of friction in the upper layers. Also as the distance of the air

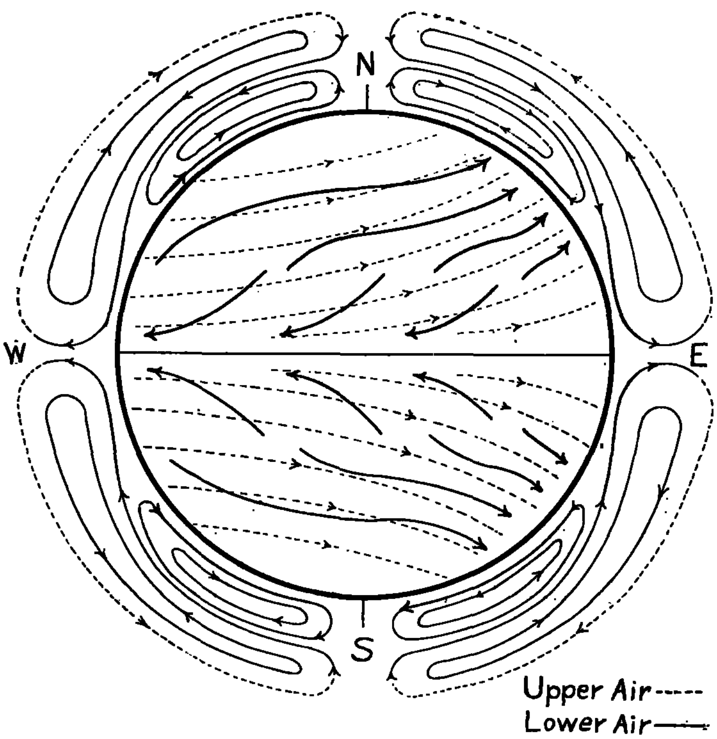

FIG. 6.—Ferrel's scheme of atmospheric circulation.

from the earth's axis decreases owing to the poleward motion, the eastward velocity must increase.

Most of the air leaving the equator must return in an undercurrent at various intermediate latitudes. Only a small share can complete the entire circuit. Also, we would expect the horizontal area of the region of upward convection to be approximately equal to that of the downward movement; thus the upward motion would extend from the equator to about latitude 30° north and south, while the remaining area, from each parallel of 30° to the poles would be a region of descending currents.

The strong equatorward deflecting force due to the high eastward velocity, serves to carry the air of intermediate elevations from the polar regions toward the equator, against the comparatively weak gradients of that region. This intermediate current continues its eastward motion until it passes the latitude of 30°, from which it moves obliquely backward (to the west) and reaches the earth's surface, becoming the northeast trade wind.

As the earth's surface is approached, the eastward velocity of the air, between latitudes 30° north and the north pole, and between 30° south latitude and the south pole, decreases because of friction to such an extent that the deflecting force is overcome by the poleward gradient and the lower air moves spirally eastward and toward the poles, becoming the prevailing westerlies.

The opposing thrusts of these winds on opposite sides of each circle of latitude 30° causes the high pressure zone along those circles, because of the deflecting force.

The low pressure at the polar regions results from the general eastward motion of the air at all latitudes and elevations outside of the zone from 30° north and 30° south. The equatorward deflecting force due to this eastward whirl reduces the amount of air in the polar regions and heaps it up toward the high-pressure zones.

Thus, this mechanical effect reverses the gradient that otherwise would result from the relatively low polar temperatures.

It is important to bear in mind that in the above rea-

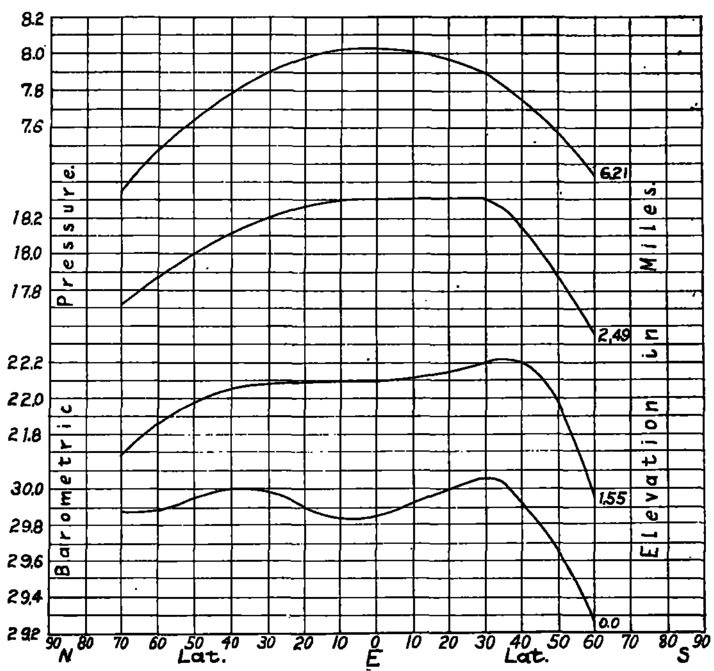

FIG. 7.—Ferrel's scheme of the distribution of pressure with elevation and latitude.

soning, which is a brief qualitative reproduction of the most important part of the elaborate investigation made by Ferrel, the earth was assumed to be a smooth rotating spheroid.

III.—REVIEW OF THEORIES THAT HAVE BEEN PROPOSED TO ACCOUNT FOR THE ORIGIN OF THE OCEAN HIGHS.

A detailed examination of the pressure distribution along parallels of latitude shows a systematic variation in pressure; meteorological charts representing yearly averages show five oceanic high-pressure areas. One is in the Indian Ocean, about half way between southern Africa and Australia; two are off the west coasts of North America and northwest Africa, at latitude 35° north; the other two are off the west coasts of South America and southern Africa, at latitude 32° south.

Humphreys (10) says: "There is, necessarily, a close relation between the location and intensities of these ocean highs and the weather of the adjacent continents, and therefore they deserve careful study. But while they themselves and their results are more or less discussed in works on meteorology, it appears that, in spite of their importance, but few attempts have been made to explain their origin."

According to Ferrel (7), a portion of the west to east winds of the higher latitudes is deflected toward the Equator by continental barriers, and thereby forced to join at each of these places the counter winds within the Tropics, producing the anticyclonic whirl on the adjacent ocean. He attributes the high pressure at the center of each whirl to the effect of the deflecting force due to the earth's rotation, and disregards the effect of temperature differences.

But, as Humphreys (10) says, the barometric high in the South Atlantic can not be accounted for on the barrier hypothesis, as the west to east winds of the southern hemisphere pass to the south of Africa in January and February. Again, if thermal causes are not a factor in producing the high pressure, it must follow that the surface winds would have an inward and the upper winds an outward velocity, which is contrary to the observed facts.

Angot (11) attributes the highs to the fact that on every parallel between the latitudes of 45° north and south, the average surface temperature of the continents is higher than that of the oceans. The pressure within the belts of highs where the atmospheric pressure is greater than that on either side is lowered over the continents and raised over the oceans, thus explaining why these belts have pressure maxima with closed isobars on the oceans.

But as Humphreys (10) says, this theory would appear to call for anticyclonic centers not far from mid-ocean, though rather nearer the largest continent. We would also expect those of the northern hemisphere to be more pronounced than the corresponding highs of the southern hemisphere, because of the greater differences in temperature due to the extensive land areas of the former. But observations show the highs to be of equal intensity in both hemispheres, and to be located near the western coasts where, for some distance inland the continents are not so warm as they are on the eastern side, which is contrary to the requirements of his theory.

Humphreys (10) calls attention to the fact that the oceanic highs are located in the high-pressure belts near the west coasts of continents, the centers of the highs being separated from the coasts by cold ocean currents. He holds that—

> The cold surface water, because of the limited amount of heat it supplies, whether by radiation or conduction, allows the air above it to cool to a correspondingly low temperature, and for any given pressure to contract and grow denser. This decreases the pressure at considerable elevations above the cold surface and allows the air to pour in from all sides, which in turn so raises the pressure at the surface of the ocean that there is a tendency for the air to flow out in all directions at the lower levels.
>
> Hence, where this cold current crosses a belt of high pressure at about 35° north or 32° south, there are two cooperating causes of high pressure: (a) The opposing thrusts of eastward and westward winds, as explained in Ferrel's theory of atmospheric circulation (5), causing a high-pressure zone and a calm belt parallel to the Equator; (b) a sheet of cold water crossing this high-pressure zone from the polar to the equatorial side, which by virtue of the cooling, increases the high at the place of crossing, and thereby produces a highest center with closed isobars and gentle anticyclonic winds.

He explains the location of the centers of the highs, which are west of the point of minimum temperature of the ocean, and therefore of the air also, by the changed direction of the winds over the coldest areas.

> Because these winds have but little east or west motion, they fail to give mechanical support to the ridge of highs, which, therefore, in part gives way at this place.

IV.—A MODIFIED THEORY OF THE ORIGIN OF THE OCEAN HIGHS.

Owing to certain objections to Humphreys' theory, I have developed a modified form of that proposed by Angot (11) in which the difference in temperature between continental and oceanic areas is regarded as the controlling factor. First let us review briefly the contrast between the land and the ocean upon which this difference in temperature depends (12).

The ocean reflects more solar radiation than the land, and is comparatively transparent, while the land is opaque, therefore the energy not reflected from the surface of the ocean is absorbed throughout a considerable depth, each layer receiving but a small fraction of the total, while a comparatively thin upper layer of land absorbs most of its incident radiation. Moreover, the land is not volatile, and therefore dry soil does not cause a disappearance of much energy as heat of volatilization, but great quantities of ocean water, by evaporating, remove a large proportion of the radiant energy received by it.

There are several other factors that combine with those mentioned to reduce both the annual and the diurnal temperature variations of water areas much below that of land areas. For example (14), the range of the annual surface temperature (29) is less than 6° over the oceans in the Torrid Zone, and less than 11° over the oceans in the greater part of each Temperate Zone, while in the surface air over the corresponding land areas the ranges are two or three times greater.

Now on the basis of Ferrel's theory (5) and the consequences of these differences between the physical properties of land and water, let us [investigate] the origin of the high off the California coast. In winter the temperature of the continent is less than that of the ocean, whereas in all seasons (13) the average wind velocity over the land is about one-half of that over the ocean. Thus the mechanical effect of the east and west components of the winds in producing a high-pressure belt is greatest over the ocean, while the difference in temperature tends to increase the pressure on the land and reduce it on the ocean.

These facts account for the approximately uniform distribution of pressure along the parallel of 35° in winter (1). But in summer, when the continents are warmer than the ocean, there must be an overflow of the upper air from the former to the latter, thus causing a decrease of pressure over the land and an increase over the ocean. Since as [in the] winter the relatively greater wind velocity in an east and west direction over the ocean operates in the same way, we would expect high pressure over the ocean having closed isobars.

Now if the temperature difference were the only factor considered we would expect, as Humphreys (10) said, to find the center of this high midway between the continents. But, owing to the prevailing eastward drift of the upper air (8), from which the descending current over the high is supplied, we would expect this downward current to have a general eastward motion as well. Thus there would be a tendency to form an anticyclonic whirl having a maximum pressure at its center, but displaced eastward toward the west coast of North America, as the charts of pressure distribution show.

The mean [wind] velocity perpendicular to a given meridian is a maximum for a meridian through the center of the high and decreases as the meridian is displaced either to the east or to the west. This is partly because the winds of the anticyclonic whirl blow to the east, north of the center and to the west, south of the center, so in each case they tend to increase the average east or west components of the general atmospheric circulation. Another reason is that the average velocity of the oceanic wind decreases toward the land to about half of its original value. There may be, as Ferrel (7) suggested, a deflection of the west wind along the coast of North America, which would cause an additional reduction of the east and west components, as the coast of California is approached. Therefore we would expect the transition from the east and west components over the ocean to their comparatively low values on land, to be more gradual toward the coast of Asia than toward the California coast only one-third as far away. These conclusions are confirmed by the charts made by Buchan (1).

The cold water bordering the California coast would tend to cool the superincumbent air and thus increase the pressure gradient near the coast, where the difference in temperature between the surface water of the ocean and the surface of the land is comparatively great. This conclusion is also verified by the same charts, and by observations made since they were prepared.

Owing to the extensive areas contributing to this convective circulation, we would expect an immense volume of air to descend to the ocean and form an anticyclone of a corresponding area. This conclusion is also supported by observations, judging from the magnitude of the areas inclosed by the closed isobars, Buchan (1).

We should also expect the center to be displaced farther from the coast as the volume of descending air increases, because of the larger area required at the bottom of this air column which must terminate at the surface of the ocean. This conclusion is verified by the fact that in summer the center is 800 miles farther from the coast than in winter. (See Buchan Chart 1.)

From the same charts, the latitude of the center of the North Pacific high, and the corresponding pressure and temperature were found, and compared with the mean pressure and temperature over a narrow belt of the same latitude in Asia and North America, for each month. The result shown by Table 1 indicates, as required by the above theory, that the pressure difference increases and decreases with the temperature difference.

TABLE 1.—*The relations between temperature and pressure.*

Month.	Temperature over—		Pressure over—		Differences.	
	Land. t_1	Ocean. t_2	Land. p_1	Ocean. p_2	t_1-t_2	p_2-p_1
	°C.	*°C.*	*Inches.*	*Inches.*	*°C.*	*Inches.*
January	12.7	18.3	30.19	30.15	− 5.6	−0.04
February	12.0	15.0	30.14	30.20	− 3.0	+ .06
March	17.0	17.2	30.06	30.25	− 0.2	+ .19
April	20.3	16.1	29.95	30.30	+ 4.2	+ .35
May	22.5	16.1	29.87	30.30	+ 6.4	+ .43
June	28.0	16.7	29.80	30.30	+11.3	+ .50
July	29.50	18.3	29.78	30.30	+11.2	+ .52
August	28.0	17.2	29.80	30.30	+10.8	+ .50
September	23.0	14.4	29.95	30.30	+ 8.6	+ .35
October	21.1	16.9	30.07	30.15	+ 4.2	+ .08
November	11.4	15.6	30.16	30.20	− 4.2	+ .04
December	8.6	12.8	30.17	30.20	− 4.2	+ .03

The relation between (p_2-p_1) and (t_1-t_2) of the above table can be approximately expressed by the equation,

$$(p_2-p_1)=0.155 \text{ inch}-0.031(t_1-t_2),$$

which shows that even when the difference in temperature is zero centigrade, the pressure exceeds that over the land by 0.155 inch. This excess, which amounts to about one-third of the maximum difference in pressure, may be accounted for by the facts that the wind velocity over the ocean surface is about twice as great as over the land surface in all seasons, and that the oceanic west wind is turned aside from its eastward course by the California coast, which acts as a barrier.

V.—DISCUSSION OF THE CAUSES OF OCEAN TEMPERATURES BEING EITHER GREATER OR LESS THAN THE AVERAGE FOR THE LATITUDE.

Let us now examine briefly the circulation and temperature of the oceans, mainly for the purpose of accounting for the presence of the cold-water regions mentioned before. Wherever the temperature of the ocean water differs notably from the average of that latitude and depth, local disturbing factors must be present.

An abnormally high ocean temperature might be the result of a flow from a warmer region; or, again, the concentration of the heat due to solar radiation, in a relatively thin layer of water might cause an abnormally high local temperature. But for depths exceeding about 100 meters the latter effect is insignificant, since nearly all of the solar rays are absorbed by that depth of water (15).

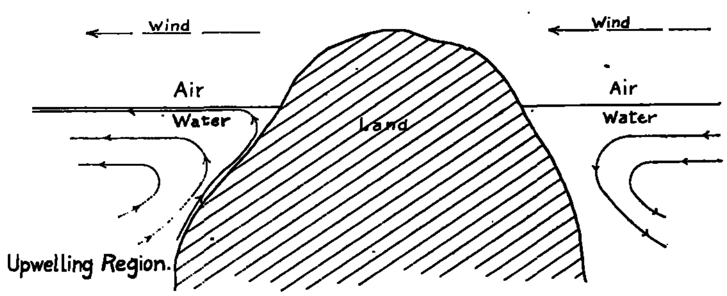

FIG. 8.—Off-shore winds and upwelling cold water. On-shore winds and warmer water.

An abnormally low temperature might be due to melting ice brought down from the polar regions, or to a current of water from a colder region. It is generally admitted that cold currents may either flow horizontally from a colder region along the surface or along any other level, or [that] they may rise from lower levels where the ocean temperature is always less than the normal for the surface at the same latitude.

The latter type of circulation is denoted by the term *upwelling*, and several examples of both kinds of circulation have been observed. Moreover, there is no general agreement as to which type, in some regions, is of the most importance or as to the cause of either.

A review of the literature shows that most authorities agree in accepting winds blowing offshore as a sufficient explanation of cold water along the west coasts of continents. Figure 8 shows how offshore winds may, by mechanically removing surface water, cause an upwelling from the bottom, and thus lower the surface temperature. Some authorities believe the cold inshore water to be the combined result of the above cause and of polar surface currents, while others regard the latter as the only cause (**2, 16, 17, 18, 19**).

But the hypothesis of offshore winds requires an extension of the trade-wind belt greatly beyond its observed limits, where calms or even on-shore winds prevail (**20**).

While polar surface currents may in some instances contribute toward these cold belts, their presence in other cases is inconsistent with the observed distribution of temperatures. For example, there are instances in which warm water extends for considerable distances in all directions from a cold inshore region. While there are other cases in which strips of alternately warm and cold water lie in a direction perpendicular to the supposed polar current (**21, 23**).

Each of the above explanations of the cold water along the west coast of North America is open to one of these objections (**21, 23**).

In order to avoid the above objections, Holway (**21**) assumed that in the northeastern part of the Pacific the drift to the east was true not only for the surface of the ocean but all the way to the bottom. Thus the cold deep water would be driven up the slope of the bottom toward the continental shelf, the effect being greatest near Cape Blanco, Oreg. (latitude 42° 50′), owing to the neighboring submarine valley. This upwelling would account for the cold surface water. However, his hypothesis does not account for the alternately warm and cold water found at various places along the coast at least as far south as latitude 28°, nor does it explain the large seasonal variation of the cooling effect (**22, 23**).

Thorade (**22**) concluded (from observations on the seasonal change in the direction of the wind and on the changes of the surface temperatures off the California coast) that the inshore cold water must be due to the upwelling of cold bottom water, caused by the component of the wind parallel to the coast. This, he said, is inexplicable without the use of a modern theory of oceanic circulation, developed by V. W. Ekman (**3**).

From the complexity of the phenomena which may produce the low temperatures, it is likely that in any given case a correct explanation can be worked out only by detailed observations of the main factors and by the application of physical principles.

VI.—Ekman's theory of oceanic circulation and its application to upwelling.

I shall now discuss briefly a part of the recent theory of oceanic circulation developed by V. W. Ekman (**3**). Although a detailed explanation of this theory involves complex problems in mechanics and mathematics, the main features of it can be given qualitatively in the following elementary manner:

Suppose a wind is blowing horizontally over the surface of a body of water, then the water will move under the action of three forces (**W**); that of the wind acting in a direction toward which the wind blows (**D**); that of the deflecting force due to the earth's rotation (see p. 16); and (**R**) [that due to] the friction of the water underneath which opposes the motion. Hence the resultant surface velocity of the water (V) will be directed to the right of the wind in order that the three forces (Fig. 9) may be in equilibrium. This surface layer of water will act upon the one underneath, just as the wind acts upon the surface layer, and so on downward. The mathematical theory shows that if we neglect differences in density, and also the influences of neighboring ocean currents and continents, the motion will correspond to the following diagram (Fig. 10). The following description may help in visualizing this motion. Imagine a spiral stairway so situated that the edge of the top step is directed at an angle of 45° to the right of the wind velocity, thus coinciding with the arrow V_0 of Fig. 10. Now if, as we descend, the successive steps are shortened so as to have

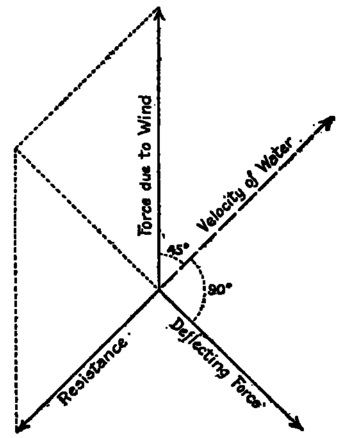

FIG. 9.—Three forces that determine the velocity of the surface water.

in succession, the lengths of the arrows in the diagram, the [length] of [each] will represent in magnitude and direction the velocity of the water at that depth. And by the time a half turn had been made the edge of the step, that is, the velocity of the water would be only 4 per cent of its value V_0 at the top, and from there downward

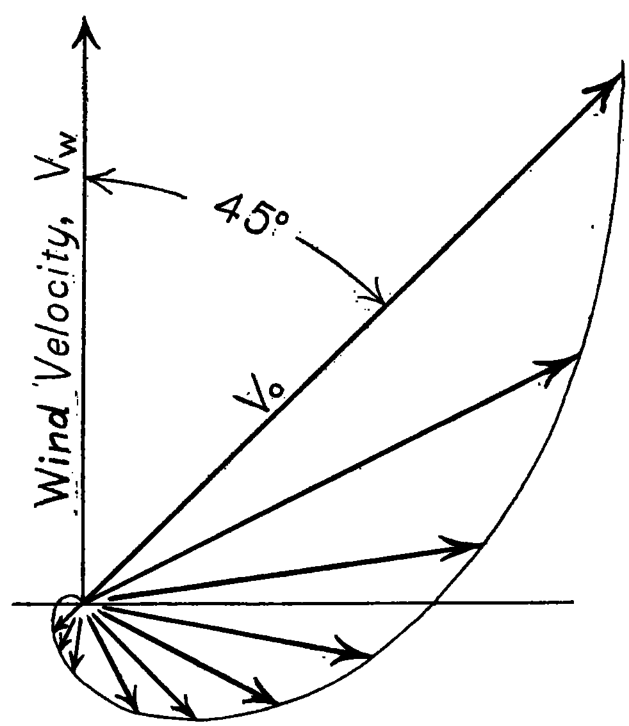

FIG. 10.—The direction and velocity of the water at increasing depths.

we would find the velocity to be still smaller. So, for practical purposes, we can neglect the motion below that point. This depth increases with the wind velocity, but decreases with the latitude. For example, at latitude 35°, if the wind velocity is 10 miles per hour, the depth (**30**) would be about 45 meters.

Suppose the wind has a component parallel to the coast line, and the water lies to the right when looking in the direction of that component. According to the previous theory, surface water will be carried to the right of and along the coast, thus causing a depression of the water level there. The corresponding reduction in pressure below the surface would cause a flow of bottom water toward the coast and upward to the surface. Thus the surface water that flows away from the coast would be continually replaced by water upwelling from the bottom (Fig. 11). Also, owing to the pressure gradient directed toward the coast, there would be a flow parallel to the coast at all depths.

In the above discussion it was assumed that the depth of the water [exceeded] about twice the depth of the wind current (**31**) and that the coast was vertical. As the depth decreases from that value the effect of the wind becomes less modified by the deflecting force, and the motion takes place according to commonly accepted laws, to which Ekman's more general theory reduces when the water is sufficiently shallow. If the coast was but little inclined from the bottom, the breadth of the upwelling region would be much greater and the vertical velocity would be proportionately reduced.

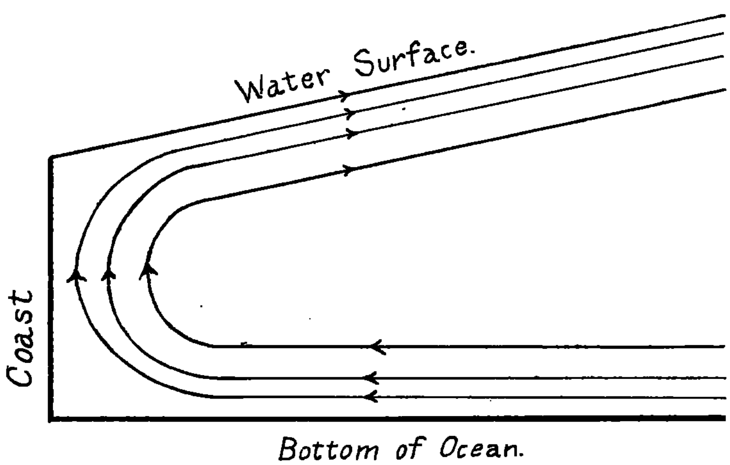

FIG. 11.—Upwelling of ocean water.

VII.—THE RELATION OF WINDS PARALLEL TO THE COAST, THE FORM OF THE BOTTOM, UPWELLING, AND SUFACE TEMPERATURES OFF CALIFORNIA.

In a former paper (**23**) I obtained, with the aid of Ekman's theory, a mathematical relation between the wind velocity, the surface temperature of the inshore water, and the normal for a given latitude.

The following table showing the data used and the results obtained, for a belt of water extending west from San Francisco, indicates the agreement between the theoretical and observed temperatures. The formula derived for this region is

$$T = (1 - 0.030\,V_w)t_2 + 0.030\,V_w t_1.$$

in which—

T is the surface temperature of the inshore water, t_2 is the normal surface temperature for the latitude, t_1 equals 8°, the mean temperature of the upwelling water (centigrade), and V_w is the component of the average wind velocity in miles per hour parallel to the coast line over an area whose center is about 400 kilometers from the coast. All of the variable quantities correspond to the same month.

Month.	V_w.	t_2.	Calculated T.	Observed T.	Differences.
	Mis./hr.	°*C.*	°*C.*	°*C.*	°*C.*
January	7.70	14.20	12.80	12.50	0.30
February	6.87	13.80	12.60	11.60	1.00
March	9.25	12.60	11.30	11.50	−0.20
April	11.40	12.00	10.60	11.30	−0.70
May	12.50	14.50	12.10	11.30	0.80
June	14.40	15.20	12.10	13.80	−1.70
July	17.50	20.00	13.70	13.50	0.20
August	18.60	19.90	13.25	13.00	0.25
September	17.60	19.90	13.60	13.80	−0.20
October	13.60	18.10	14.30	14.60	−0.30
November	8.80	16.60	14.30	13.90	0.50
December	6.65	15.20	13.80	13.40	0.40

Since the upwelling is more concentrated, the more rapidly the depth increases with the distance from the coast, we would expect the reduction of the surface temperature to be correspondingly greater. Also, we would expect the temperature to increase along a horizontal line running out from the coast. Both of these conclusions agree with the results of observations off the California coast (**23**).

VIII.—RÉSUMÉ AND FINAL APPLICATIONS OF THE PRECEDING RESULTS.

The results of the preceding investigation may be condensed into the following eight propositions:

1. The west winds (**32**) north of latitude [35° north] press southward, while the east winds, south of the same parallel, press to the north, because of the deflecting force due to the earth's rotation.
2. The side thrusts of these winds give rise to a belt of high average air pressure between the east and west winds, at latitude 35°, but the average wind velocity is about twice as great over the ocean as over the land; also, the west wind is deflected partly to the north and partly to the south, by the west coast of North America.
3. Thus the mechanical effect of the winds in producing the high air pressure is always greater over the ocean than over the land.
4. In summer there is an overflow of the upper air from the warm land surface to the comparatively cool surface of the ocean, while in winter, when the land is colder, this circulation is much weaker, or may even be reversed.
5. Therefore, in summer, the mechanical and thermal causes combine in producing a high-pressure area over the Pacific Ocean, and low pressures over the continents of Asia and North America; but in winter the mechanical and thermal causes are opposed, thus giving rise to an approximately uniform pressure along the circle of latitude 35°.
6. Because of the prevailing eastward drift of the upper air from which the descending current (over the Pacific Ocean) is supplied, the center of the high-pressure area is displaced to the east, but remains far enough from the west coast of North America to allow the descent of the immense volume of air to the ocean. The distance from the center to the coast varies from 800 to 1,500 miles.
7. Because of the spiral motion of the air outward from this center, and the southward deflection of a portion of the west winds, there is a broad belt of northwest winds along the California coast. The velocity of these winds is greatest in summer and least in winter.
8. These winds produce an upwelling of the bottom water adjacent to the coast at a rate proportional to their

velocity parallel to the coast, thus cooling the surface and causing a general drift to the southwest of this surface water, whose temperature is lowest at the coast and increases from there with the distance from the coast.

From the above propositions we see that the periodic cooling of the inshore water off the coast of California is caused largely by the Pacific high-pressure area, whose intensity depends upon the varying heat of the sun through the months of the year, and upon the difference in temperature and wind velocity due to the contrast between land and water surfaces.

Let us now consider some of the objections to Humphreys' theory of the origin of the ocean high off the California coast. The area of the California cold-water belt (23) appears to be too small to produce the large area of high air pressure shown by observation (1). The center of the high is 1,500 miles west of the region of minimum

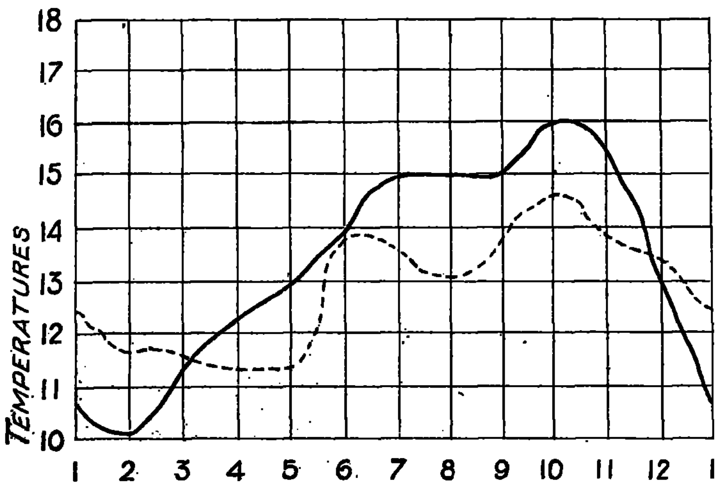

FIG. 12.—Cool summers at San Francisco controlled by adjacent ocean temperatures. ...... ocean temperatures, ——— air temperatures.

temperature in summer, while the maximum width of the cold-water belt scarcely exceeds 1,200 miles (1, 23). But the main objection is that the upwelling theory just explained shows that the existence of the sheet of cold inshore water depends upon the coast winds, which in turn are largely due to the Pacific high. Therefore the sheet of cold water which Humphreys claims is the cause of the [North Pacific] high is really one of its effects.

An inspection of the charts (1) showing the average monthly pressure, wind velocity, and temperature of the world indicates that the other three highs and cold-water belts may be accounted for by a theory similar to the one just applied to the North Pacific ocean. And, judging from the results already obtained, the general problem of ocean highs and cold-water belts is a profitable field for further investigation.

On the California coast, the prevailing wind over the land blows from the west of north except during a part of the winter. We would expect from this fact that, between the ocean and the mountains, the climate, except possibly in winter, would be largely controlled by that of the adjacent surface water of the ocean. The observations represented by figures 12 and 13 verify this conclusion, at least as far as temperature is concerned. Thus the well-known cool summers at the California coast are due largely to the cold inshore water, whose low temperature is indirectly caused by the relatively hot continental areas of Asia and North America.

IX.—SUMMARY.

1. The uniform high-pressure belt along each of the circles of latitude 32° north and 35° south, which would be formed if the earth's surface were homogeneous, is actually broken up into several areas of relatively high and low pressure.

2. This break in the continuity of pressure is partly due to differences in the physical properties of land and water areas, which give rise to an unequal temperature distribution along parallels of latitude, the land being the warmer [area] in summer and the cooler one in winter. Also, the relatively high east and west components of the wind velocity over the ocean, as compared to those over the continents, tend to cause a continual excess of pressure on the ocean over that on the continents.

3. Barometric observations over Asia, the North Pacific ocean, and North America show that the above difference in wind velocity combines with the seasonal temperature differences between the ocean and the land in such a way as to produce an approximately uniform high-pressure belt along the parallel of latitude 32° in winter, while in summer the cooperation of the mechanical and thermal causes gives rise to a high with closed isobars over the ocean.

4. The periodic variation of the intensity of the North Pacific high gives rise to an extensive periodic anticy-

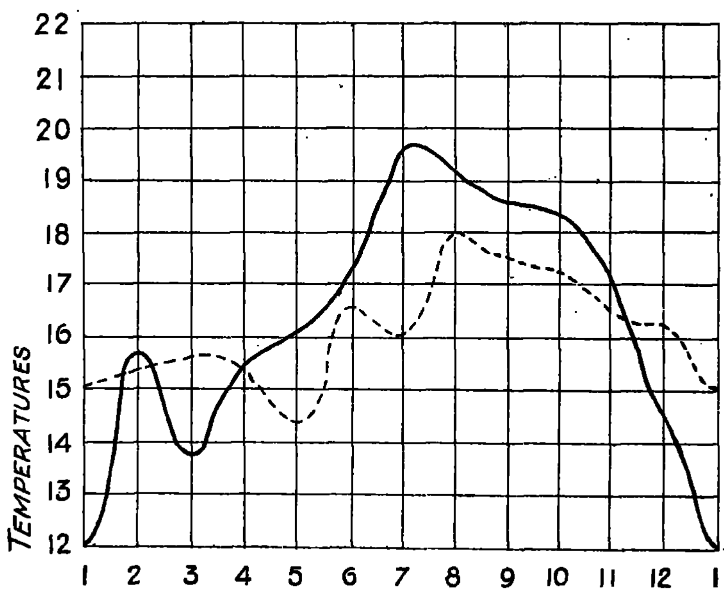

FIG. 13.—Cool summers at San Diego due to cold on-shore winds. ...... ocean temperatures, ——— air temperatures.

clonic whirl off the California coast, of which the prevailing winds blowing from the west of north, along the coast, are a part.

5. These winds produce an upwelling of cold bottom water along the coast at a rate proportional to their velocity parallel to the coast, and thus reduce the surface temperature of the inshore water sufficiently to produce the well-known cold-water belt off California.

6. The climate of that part of California lying between the coast and the mountains is largely controlled by the surface temperature of the adjacent ocean, and consequently agrees at any place with the normal marine climate of that latitude in winter. But in summer, when the upwelling is so pronounced as to reduce the surface

temperature of the inshore water much below the normal, a coast climate, peculiar in many respects, is produced, the remarkably low summer temperature being the most striking peculiarity.

7. Thus the "Egyptian winters and Alaskan summers" (**24**) experienced in San Diego are explained as a necessary consequence of the operation of physical laws in connection with the distribution of land and water areas, hence the stability of the climate of San Diego is comparable with the stability of the present geological features and astronomical configuration.

In conclusion, I wish to thank Dr. W. E. Ritter and Mr. E. L. Michael for their suggestions relative to the presentation of the subject in a form comprehensible to the general reader, and Mr. C. J. Marvin, of the Scripps Institution, for his assistance in making the drawings.

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(**25**) The *pressure gradient* or *barometric gradient* is the rate at which the pressure decreases in going a unit distance horizontally along a level surface from a place of high to one of low atmospheric pressure, or vice versa.

(**26**) Under these conditions, a plumb line would coincide with the earth's radius produced through the point of suspension.

(**27**) The trade-wind theory advanced by George Hadley (**9**) required a steady increase in pressure from the equator to each pole, according to the observed decrease in temperature. But barometric observations taken from 1839 to 1843 (**4**) contradicted this theory, and the general problem of pressure distribution and atmospheric circulation remained inexplicable until Ferrel developed his theory of atmospheric circulation during the period from 1856 to 1882.

(**28**) Atmospheric pressure is expressed in inches of mercury throughout this paper.

(**29**) The centigrade scale of temperature is used throughout this paper.

(**30**) The general relation is D (in meters) $= \frac{3.4}{\sqrt{\sin L}} W$, where L is the latitude and W is the wind velocity in miles per hour.

(**31**) Wind-current is a technical term used to denote the current in the upper part of the water, produced by a wind under the conditions assumed on p. 20.

(**32**) The wind blows *from* the direction named.

LORIN BLODGET'S "CLIMATOLOGY OF THE UNITED STATES": AN APPRECIATION.

By ROBERT DE C. WARD.

[Dated, Harvard University, Cambridge, Mass., Sept. 22, 1913.]

So impossible is it to keep our heads above the rising tide of the new meteorological literature that we are neglecting, to our loss, the rich stores which lie buried in the books of a generation ago. The name of Lorin Blodget is probably known to Americans chiefly through their reading of the sections on the United States in Dr. Hann's *Handbuch der Klimatologie,* where the ranking meteorologist of to-day makes appreciative reference to, and quotation from, the work of our pioneer American climatologist. Yet Blodget's discussion was of fundamental importance, and is, even now, worthy of the attention of all our students of climatology.

During the short semi-vacation of the past summer, spent among the New Hampshire hills, I have turned again to Blodget's *Climatology of the United States* for relaxation and for instruction. More than ever before, I am impressed by the labor involved in the preparation of this book; by the author's broad and clear view of his subject; and by the practical application of the facts. My rereading of this book has given me new light on my path as a teacher. And I hope that this notice may turn attention once more to the importance of Blodget's work for American climatology, and may help to preserve for this almost forgotten author of 50 years ago the place to which he is entitled among American meteorologists.

It was no easy task which Lorin Blodget set for himself.[1] It would have discouraged many men. But Lorin Blodget did it. And he did it well. No one else has attempted, much less carried through, so ambitious an investigation. Gratefully, and gracefully, does our author acknowledge his indebtedness to Alexander von Humboldt, whose "models were his guide" and whose "tone of generalization" it was Blodget's "highest ambition to attain." Out of the confused mass of scattering observations which had been accumulating from different sources at the Smithsonian Institution and the Office of the Surgeon General, and from "gentlemen at distant points distributed over the country," Blodget brought

[1] The full title of the book is as follows: "Climatology of the United States, and of the Temperate Latitudes of the North American Continent: Embracing a full comparison of these with the Climatology of the Temperate Latitudes of Europe and Asia, and especially in Regard to Agriculture, Sanitary Investigations, and Engineering, with Isothermal and Rain-Charts for each Season, the extreme Months, and the Year. Including a Summary of the Statistics of Meteorological Observations in the United States, condensed from recent scientific and official Publications." (Philadelphia, J. B. Lippincott & Co.: Trübner & Co., London, 1857. xvi, [17]–536 p. 4°.)